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HETEROEPITAXIAL InP, AND ULTRATHIN, DIRECTLY GLASSED, GaAs III-V SOLAR CELLS.

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Abstract:

The commercial application of Indium Phosphide solar cells in practical space missions is crucially dependant upon achieving a major cost reduction which could be offered by heteroepitaxy on cheaper, more rugged substrates. Furthermore, significant mass reduction, compatibility with mechanically stacked multijunction cells, and elimination of the current loss through glue discoloration, is possible in III-V solar cells by the development of ultrathin, directly glassed cells.

This paper describes the progress of a UK collaborative program to develop high efficiency, homojunction InP solar cells, grown by MOCVD on Si substrates. Results of homoepitaxial cells (>17% 1 Sun AM0) are presented, together with progress in achieving low dislocation density heteroepitaxy.

Also, progress in a UK program to develop ultrathin directly-glassed GaAs cells is described. Ultrathin (5 micron) GaAs cells, with 1 Sun AM0 efficiencies up to 19.1%, are presented, together with progress in achieving a direct (adhesive-less) bond between the cell and coverglass. Consequential development to, for example, cell grids, are also discussed.

Keywords:

InP, GaAs, Heteroepitaxy, Ultrathin, Direct Glassing.

III-V solar cells vs Si.

It is well established that some III-V solar cell materials, such as GaAs or InP, offer substantial performance improvements over conventional Si cells, due to three main reasons [ref 1]. The band-gap for both materials is closer to the optimum for single-cell performance - in the case of GaAs (1.43eV) the maximum predicted beginning-of-life (BOL) 1 sun AM0 efficiency is as high as 26% compared to a more modest predicted maximum of around 22% for Silicon.

Secondly, it is well established that some III-V solar cell materials offer much higher radiation resistance, compared to conventional Si cells, which enhances their relative performance at end-of-life (EOL). This is a very significant factor, particularly for InP which appears to have higher radiation resistance than other materials.

Thirdly, the degradation in performance at elevated temperatures, for the higher bandgap cell such as GaAs, is much smaller than for Si cells.

Furthermore, some III-V solar cell materials, including both GaAs and InP, have a direct band-gap. The consequences of this are much high absorption coefficients than is the case for indirect band-gap materials such as silicon. Thus all the light useful to the cell is absorbed within the first few microns, resulting in the bulk of the cell material being redundant, leading to the possibility of ultrathin (<10 micron) cells.

InP Solar Cell types:

There are three main types of InP cell. These comprise the epitaxially grown cells, (by MOCVD, MBE or related growth techniques), diffused junction cells (in which the junction is formed within the bulk substrate by diffusion), and surface junction cells, where the junction is formed substantially at the surface, by deposition of material (eg Schottky barrier type cells, or ITO cells).

The present program [1]addresses both epitaxially grown cells (MOCVD growth, both homoepitaxial and heteroepitaxial), and ITO/InP cells heteroface cells.

ITO/InP cells:

The Indium Tin Oxide /InP (ITO/InP) solar cells under consideration within the present program comprise an RF sputter deposited layer of ITO on p-type InP (Figure 1), and have been discussed more fully previously [ref 2-4]. Analysis of eg CV measurements leads to the theory that a shallow homojunction cell is formed, through the creation of a damaged layer just underneath the surface. The potential advantage of such cells is that the requirement for expensive epitaxy processing is redundant, although to-date, BOL efficiencies achieved with this type of cell have, in general, been lower than for epitaxial cells.

Epitaxial InP cells:

The epitaxial cells upon which the program has focused are shallow homojunction n^+-p-p^+ cells, fabricated with a lattice-matched InGaAs cap layer (Figure 2), with efficiencies approaching 18% 1 sun AM0 BOL (Figures 3, 4). The program baseline is 2x2 cm cells. The baseline cell structure has been established following pseudo-three dimensional modelling of the cell [ref 7]; this has incorporated lifetime values derived from test structures closely emulating the cell conditions. Furthermore, series resistance effects have been accurately taken into account using a distributed element approach, resulting in better optimisation of collection grid design.

Irradiation Studies:

1 MeV electron irradiation studies have been carried out on both types of cell; further electron and proton studies are scheduled for autumn '92, and spring '93. As expected, both types of cell stand up well to electron irradiation, better than either Silicon or GaAs [refs 5,6], with over 75% power remaining after a dose of 1E15 electrons (bare cells, in the dark) (Figure 5). The evidence suggests that still lower degradation is experienced for cells under load [ref C]. Furthermore, significant recovery of the cell parameters has been achieved at moderate temperatures (90^{o}C).

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Commercial Applicability:

In order for Indium Phosphide solar cells to be commercially applicable for practical space missions their cost must be significantly reduced below current levels. The (significant) cost of epitaxy can be eliminated through use of ITO/InP cells as described above, or diffused junction cells. (For example, the only mission to baseline InP cells for power production is the Japanese MUSES-A lunar orbiter using 1x2cm diffused junction InP cells [ref 8].) However, performance of the former type of cell has so far failed to match that of epitaxial cells, the cells on MUSES-A averaging 16% (BOL).

The cost of InP cells is heavily dependant on material costs. Thus the greatest cost benefit will be through heteroepitaxy on cheaper, more rugged, substrates. To this end, the program includes development of InP grown heteroepitaxially on Si (with and without intermediate layers).

InP/Si Heteroepitaxy:

The critical problem to be addressed in heteroepitaxy is how to accommodate lattice mismatch between the different materials. In the case of InP (5.869Å) on Si (5.431Å), this amounts to some 8%. The approaches being considered, within the present program, to accommodate this include: (a) direct growth of InP on Si via a "two-step" growth process; (b) growth of InP/GaAs/Si via a double "two-step" process, and (c), growth of InP/GaInAs/GaAs/Si, where the InP is grown on graded-composition InGaAs, (0-53% to provide lattice matching at the InP interface).

Experiments have confirmed the critical nature of the mismatch, with dislocation densities 2 orders of magnitude higher than acceptable being obtained for graded layers, and polycrystallinity evident on InP/Si.

However, for the case of InP/GaAs/Si, initial growths have produce films giving double crystal x-ray rocking curves with FWHM of 500 arc sec, and FWHM of 320 arc secs has been achieved with post-growth annealed samples, (although it is possible that the reduction seen on annealing is due to twin annihilation, which gives rise to threading dislocations, and therefore will not provide "better" material quality than that in the un-annealed state). Furthermore, growth of the intermediate GaAs layers on Si has produced x-ray FWHM of 152 arc sec.

Ultrathin InP Cells:

One of the potential advantages of heteroepitaxial InP is the possibility of removing the bulk of the heteroface material, leaving an ultrathin (5-10 micron) cell. This will facilitate mechanically stacked multijunction cells, with little sub-bandgap absorption in the InP cell.

However, some manufacturing issues in ultrathin InP cells remain to be addressed, such as interconnection techniques, supporting structure, etc. These issues are already being addressed for (related) ultrathin GaAs cells.

Ultrathin GaAs cells:

Several workers have already reported ultra-thin GaAs solar cells [refs 9-13]. EEV have been developing chemically etch-stopped GaAs cells grown on GaAs and Ge [ref 11], and have produced ultrathin (8 micron) cells up to 19.7% efficient, based on measured cell area of 3.7cm^2 (Figure 6). The technology is readily transferable to heteroepitaxial InP cells.

Directly Glassed GaAs cells:

Critically important for their use, is the ability of ultrathin cells to withstand handling and integration processes. Furthermore, one of the causes of current degradation over a cell's lifetime in space, is discoloration of the coverglass adhesive. These two issues combine, to raise interest in adhesiveless bonding of cells. One technique that has been tried is use of teflon bonding [refs 11,14]; however, of more interest is the possibility of completely doing away with any bonding medium, and relying on a direct bond between the coverglass and cell [ref 12].

This approach has been greatly facilitated by the advent of a coverglass material with expansion coefficient matched to GaAs [ref 15], and EEV are involved a program [2]to develop direct glassing of ultrathin GaAs cells, following on from the adhesive-bonded ultrathin work. The bond is formed by ionic diffusion formed by an electrostatic field applied during compression at elevated temperatures, requiring the cell to withstand somewhat higher temperatures than standard for a short time (seconds/a few minutes).

Interconnecting ultrathin Cells:

The ease of interconnection of such cells is under consideration; when made in conjunction with direct glassing, there is no adhesive-matrix to support the interconnect near the cell, and the problems associated with the interconnect flexing and cracking the cell are significant. The option of providing interconnection via metal attached to the coverglass rather than (primarily) to the cell is being considered (figure 7).

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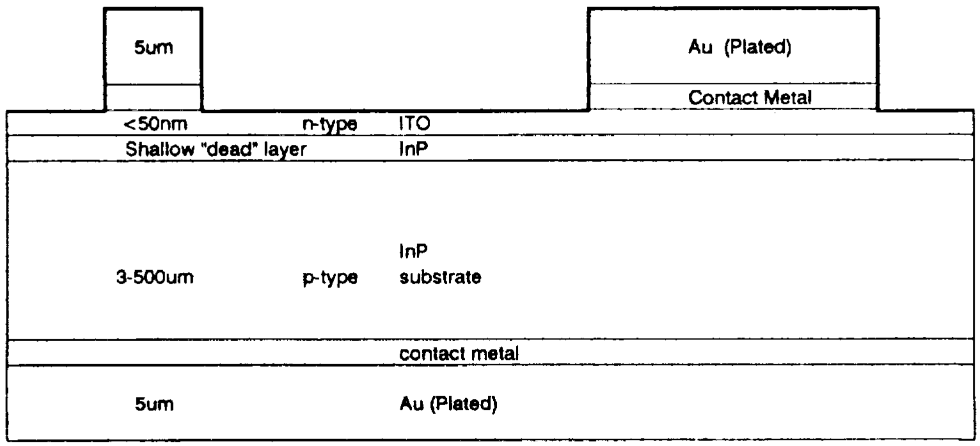

Figure 1: Schematic of ITO/InP Solar Cell

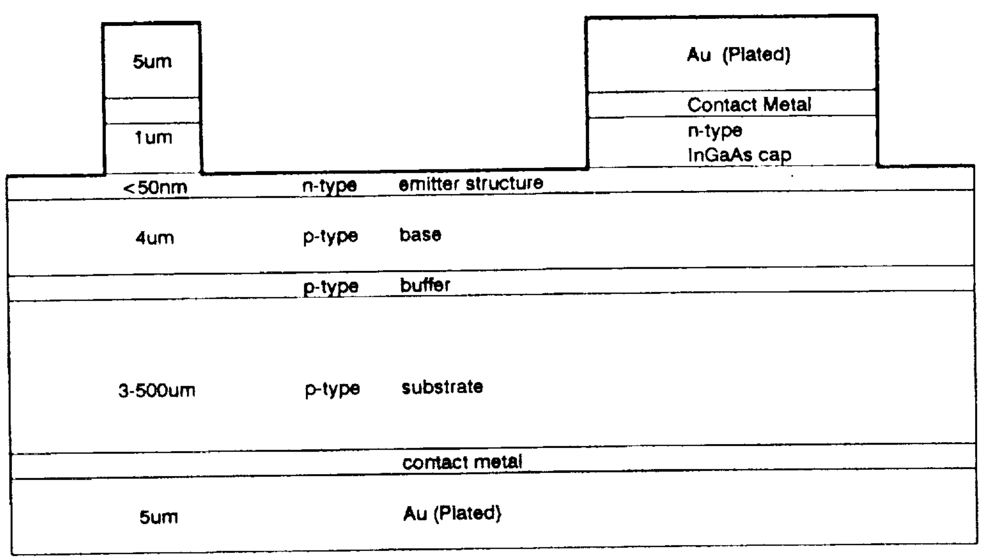

Figure 2: Schematic of Epitaxial InP Solar Cell

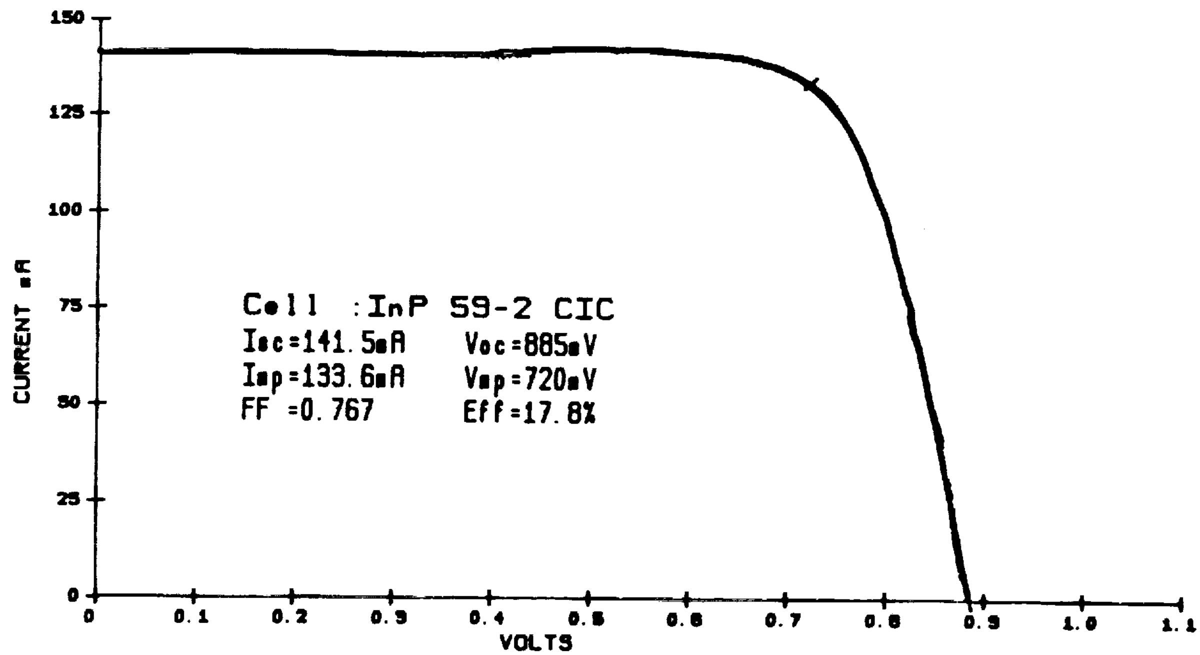

Figure 3: 1 Sun AM0 Photovoltaic measurement of 2x2 cm homoepitaxial n^+-p-p^+ Solar Cell

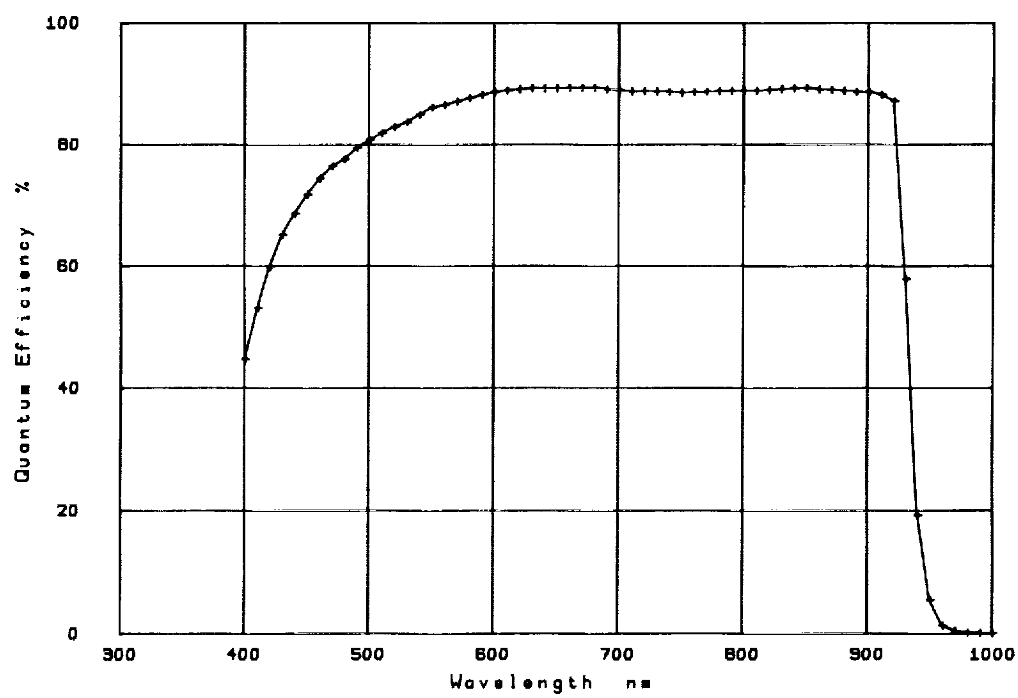

Figure 4: Quantum Efficiency of 2x2 cm homoepitaxial n^+-p-p^+ Solar Cell

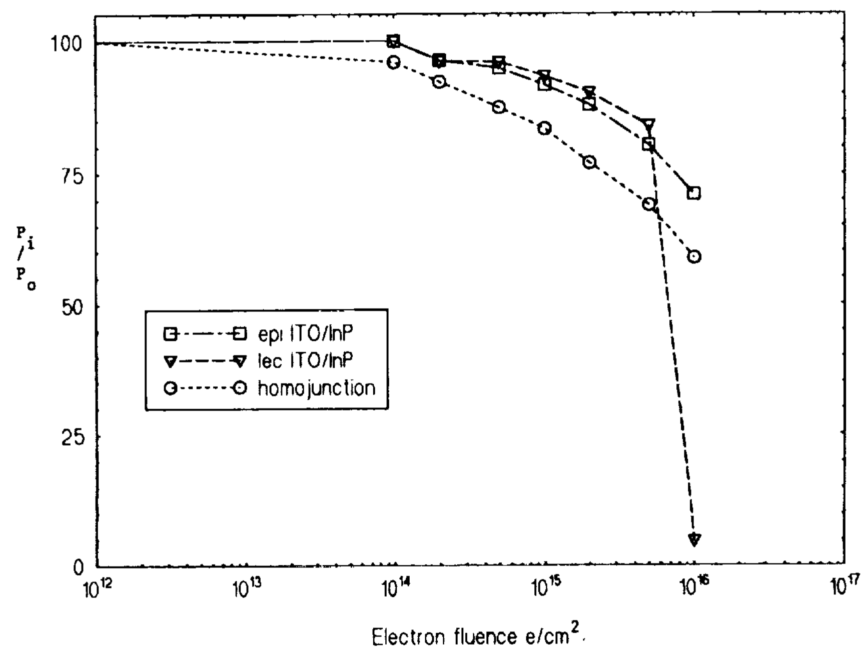

Figure 5: Percentage Power remaining for InP Solar Cells after 1 MeV electron irradiation.

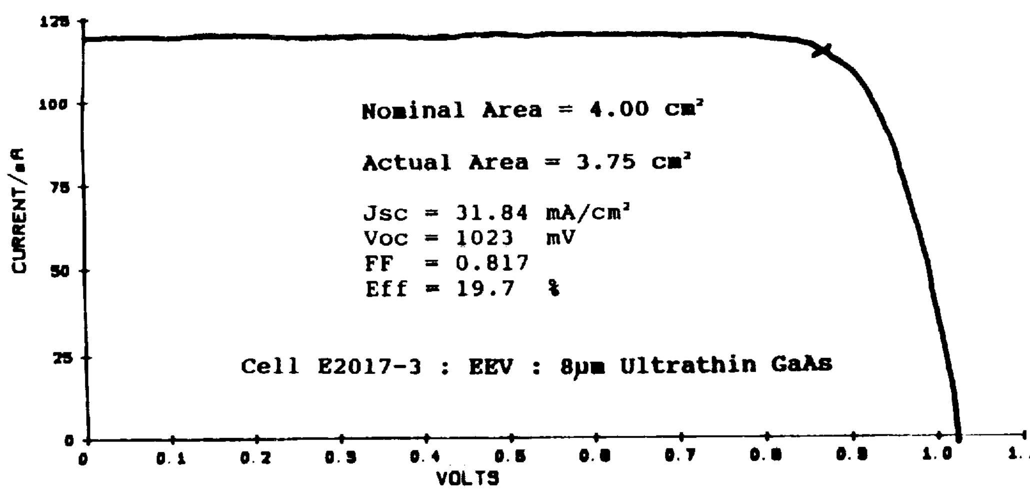

Figure 6: 1 Sun AM0 Photovoltaic measurement of 2x2cm ultrathin GaAs Solar Cell

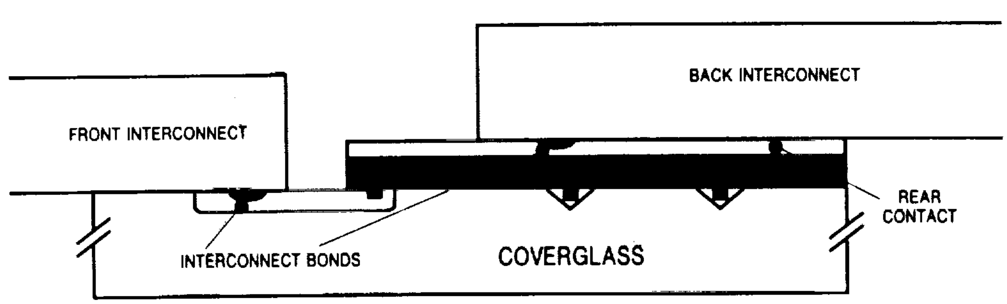

Figure 7: Interconnection to an ultrathin GaAs (or InP) cell, with interconnect supported on the coverglass.